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THE FEASIBILITY OF STUDYING ATMOSPHERIC POLLUTION WITH SATELLITES

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ABSTRACT. A review is given of papers, which are devoted to studying the possibilities of determining the gaseous components (sulfur dioxide, carbon monoxide, etc.) of atmospheric pollution from spectral measurements of the emitted thermal radiation. The available data show that this problem can be solved in principle. The necessity of a complex approach to solving this problem is discussed, and its close relation to the problem of thermal satellite sounding of the atmosphere is noted. /3**

In spite of the strict measures, which have been applied to reduce industrial atmospheric pollution, the pollution problem has become ever more serious, and sometimes reaches dangerous proportions (especially near industrial centers). It has been established, for example, that the meterological conditions in many cities now depend on the pollution of the air to a significant degree [1, 7]. The results of atmospheric pollution can be even more serious, especially in several countries of Western Europe.

Figure 1 shows that these conclusions are correct, as related to West German data on the increase of the number of automobile drivers, the growth in electrical and petroleum requirements, and the population growth [7]. It can be seen that a linear population growth is accompanied by an exponential growth in the factors that cause atmospheric pollution.

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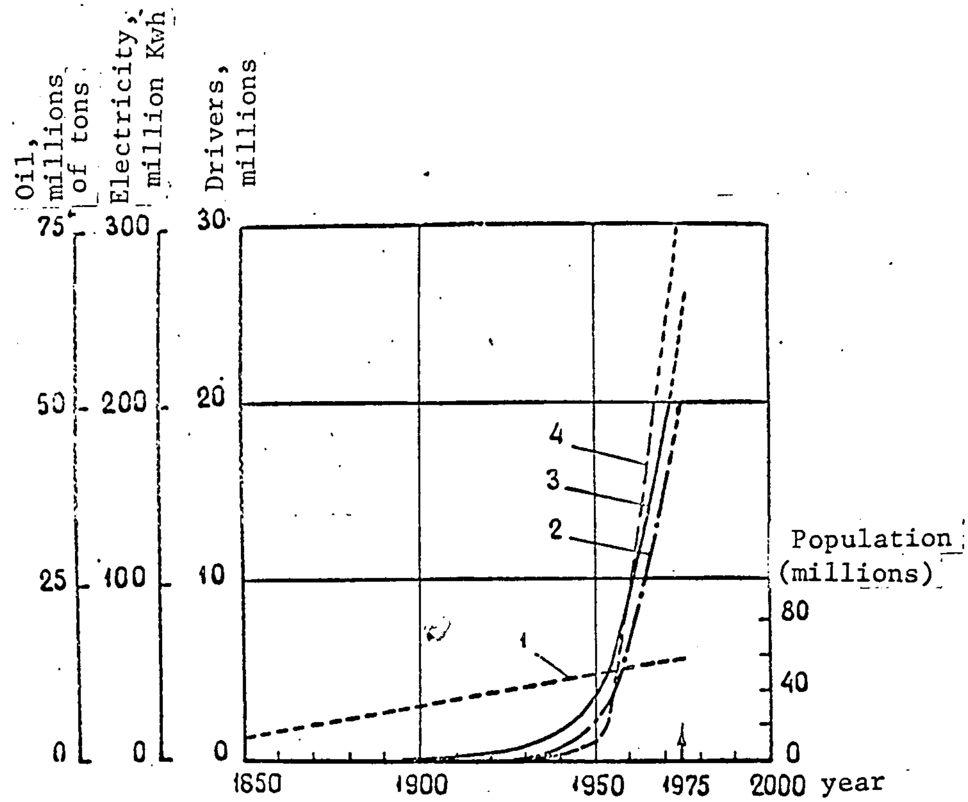

Figure 1. Increase in the demand for electricity and petroleum in West Germany, compared with the population increase.

The rapid development of all types of transport (primarily automobile and air transport), and also the intensive growth of industry, leads to an increased level of atmospheric pollution not only in the immediate neighborhood of large industrial centers, but also in a much larger territory. The pollution from high-altitude jet aircraft, and also from satellite launchings, is distributed in the upper layers of the atmosphere [6]. All of these factors lead to a pollution problem of truly global proportions, and make it necessary to investigate the feasibility of using satellite methods for studying atmospheric pollution.

Spectrophotometric observations of the twilight halo of the earth from a manned orbital station [4] are important for studies of the dust concentration of the atmosphere at various altitudes. However, we shall concentrate on only problems of the gaseous components of atmospheric pollution.

Atmospheric pollution consists of primary polluting components in the atmosphere, as well as secondary products, which arise from various chemical and photochemical reactions. The main components of pollution include compounds of sulfur (mainly SO_2), nitrogen (NO, NO_2, NH_3), carbon (CO, CO_2), halogens, hydrocarbon compounds, aldehydes, and particles (solid aerosols). CO, SO_2, NO_2, and O_3 are the most characteristic components of industrial pollution. Table 1 shows comparative data which characterize sample concentrations of polluting components in a pure and a polluted atmosphere [7]. In all cases, except for aerosol pollution, the quantities are volumetric concentrations expressed as ten-thousandths of a percent (ppm). /4

TABLE 1. CONCENTRATION OF POLLUTING COMPONENTS
IN A PURE AND A POLLUTED ATMOSPHERE

Polluting component	Pure atmosphere	Polluted atmosphere
Sulfur dioxide	0.001 to 0.01	0.02 to 2
Carbon monoxide	< 1	5 to 200
Carbon dioxide	310 to 330	350 to 700
Nitrogen oxides	0.001 to 0.01	0.01 to 0.1
Hydrocarbon compounds	< 1	1 to 20
Aerosol pollution mg/m^3	0.01 to 0.02	0.07 to 0.7

It can be seen that the concentration of carbon monoxide exceeds the total concentration of all other components (except for carbon dioxide). Sulfur dioxide and hydrocarbon compounds should be regarded as the second most important polluting components. A characteristic "dome" of pollution lies above large industrial centers; its height can reach 1000 meters, and usually exceeds 500 meters. /5

Various methods of using satellites can be postulated for observing and determining the concentration of polluting components in the atmosphere. For example, when the solar rays pass through the atmosphere, it is possible to record the absorption spectra of solar rays passing through the atmosphere at sunrise and sunset relative to the satellite [2]. However, it is obvious that this method cannot be used for the lower atmospheric layers, where the attenuation of the radiation is too large, and thus the measured signal is practically zero. However, it is the investigation of the lower atmospheric layers that is of greatest interest.

If measurements are made of the solar radiation, that is reflected and scattered by the Earth in the ultraviolet and visible range of the spectrum, then it is possible to try to use the spectral characteristics of the emitted short-wave radiation, which is caused by the existence of absorption bands for a series of polluting components (mainly SO_2, NO_2, and O_3). However, practical application of this method is complicated by the fact that these spectral characteristics are rather weak, while data interpretation is complicated by such factors as reflection from the surface of the Earth and scattering (and also absorption) by solid aerosols. These factors are very variable, and have a significant effect on the field of emitted radiation. This situation is further aggravated by the fact that the above-mentioned gases have most of their absorption bands in the ultraviolet and visible regions of the spectrum (300-655 mμ), where the factors that confuse data intepretation are the strongest.

Possibly the most promising method is to interpret the measured data in the ultraviolet and visible spectra by means of a "correlation" method [6]. This method uses a "correlation" spectrometer in which the measured spectrum of the emitted radiation is "modulated" by a comparison spectrum. Both spectra are compared by the beat of the output signal. The amplitude of this signal gives a quantitative measure of the concentration of the desired component in the atmosphere. Airplane experiments of a similar method, whose goal was to determine the concentration of sulfur dioxide (from data measured near the 3150 Å wavelength) gave promising results.

The development of satellite meteorology has convincingly shown that the most promising method, for solving problems which are related to the study of atmospheric structure and composition, uses spectral data from measurements of the emitted thermal radiation [3]. It is possible to verify that this conclusion is correct and can be applied to determine the composition of atmospheric pollution. We can show that this conclusion is true by using some results of recent studies [8].

C. B. Ludwig, R. Bartle, and M. Griggs [8] carried out numerical experiments to evaluate the effect on emitted radiation of the presence of a pollution layer (near the Earth's surface) 300 meters thick. They used the following atmospheric stratification model: the ARDC-1959 standard atmosphere, the artic /6 winter atmosphere, and the tropical atmosphere. Figure 2 shows calculated results for the 4.6 μ carbon monoxide band for insignificant (1 ppm), average (10 ppm), and highly polluting (100 ppm) concentrations of CO. The relative emittance of the Earth's surface was taken to be 0.95. The calculations were performed for various values of the Earth's surface temperature T_s (for determining the influence of the 24-hour temperature variation) and an average temperature of the polluted layer $\bar{T}_a$.

TABLE 2. VARIATION IN THE INTENSITY OF EMITTED RADIATION ΔI_∞ NEAR THE 4.6 μ WAVELENGTH IN THE PRESENCE OF A POLLUTING LAYER OF CARBON MONOXIDE

Atmosphere	Carbon monoxide concentration, ppm	ΔI_∞,%
Standard	1	0.05
T_s = 288°K	10	0.26
$\bar{T}_a$ = 287°K	100	0.80
Standard	1	1.85
T_s = 298°K	10	6.56
$\bar{T}_a$ = 287°K	100	16.63

Atmosphere	Carbon monoxide concentration, ppm	ΔI_∞,%
Standard	1	-2.65
T_s = 278°K	10	-9.20
$\bar{T}_a$ = 287°K	100	-22.96
Tropical	1	0.02
T_s = 305°K	10	0.06
$\bar{T}_a$ = 304°K	100	0.32
Artic Winter	1	-1.74
T_s = 247°K	10	-6.49
$\bar{T}_a$ = 251°K	100	-16.98

Naturally, the "sensitivity" of the emitted radiation to the concentration of the polluting component depends to a significant degree on the temperature difference $T_s-\bar{T}_a$. For small temperature differences, ΔI_∞ does not exceed the measurement error limits (available apparatus makes it possible to have measurement accuracies of no better than 0.5 to 1% [5]). However, this sample calculation on the whole gives promising results for one of the most important polluting components.

The effect of the vertical concentration profile of the polluting component on the amount of the emitted radiation was also studied (for a constant overall concentration) [8]. Detailed calculations of this type were done for ammonia (wavelength 10.8 μ). These calculations showed a significant dependence of the emitted radiation on the vertical distribution of the pol- /7
luting component.

Figure 2 shows the calculated spectral distribution of the quantity $\Delta I_\infty(\lambda)$ as a function of the wavelength for eight polluting components, both separately and also the total effect of all these components (of course, the total effect is not additive) for the standard atmosphere. The spectral /8

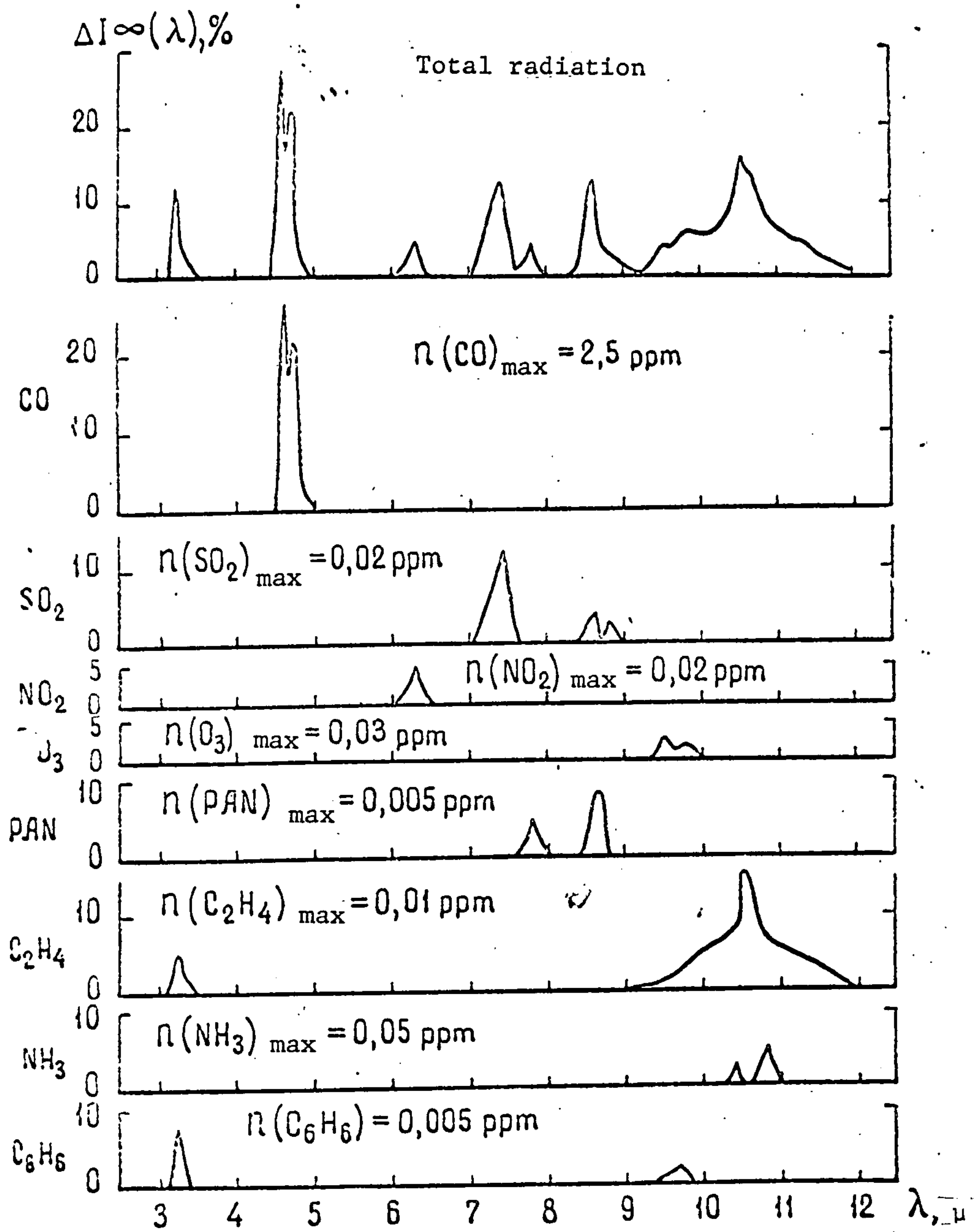

Figure 2. Change in the emitted radiation $\Delta I_{\infty}(\lambda)$ for various polluting components as a function of wavelength (PAN - Peroxyacetylene nitrate).

resolution was 0.1 μ. The maximum gas concentrations n_{max} shown in Figure 2 correspond roughly to one tenth of the concentration that is typical of moderate and heavy pollution levels at the Earth's surface. It can be seen that the total curve clearly shows the peaks that correspond to carbon monoxide and sulfur dioxide.

The data of Figure 2 clearly show that the overlapping of the emission bands of the separate gases is a complex problem. Naturally, the situation is further complicated if the curves include the effects of bands which have been neglected in these calculations, especially the effects of water vapor and carbon dioxide. From this, it follows that the first requirement for successfully determining the composition of polluting components from data on the measured emitted radiation is to find a spectral interval where the absorption spectra of this and other components do not overlap. Obviously, this condition can be most reliably realized by chosing a sufficiently narrow spectral integral.

Since the emitted radiation is mainly determined by the vertical distribution of the irradiating component (in the absence of overlapping bands) and the temperature, it follows that the first step in determining the vertical concentration profile of a polluting component is to measure the variation of temperature with altitude. Since the problem of using satellites to thermally sound the atmosphere is practically solved (see [13]), this does not cause any special difficulties. Moreover, the mathematical methods, which were developed for solving thermal sounding problems, can be applied to interpreting the measured data from the emitted radiation in order to determine the composition of polluting components.

Here it is very important to observe the essential dependence of the solution of the reverse problem of satellite meteorology on the accuracy of the kernel used in the integral equation in the problem. That is, the derivative of the transmission function must be reliably known. The significant data on the above-mentioned transmission functions of the polluting components are only very approximately known. Thus it is indisputable that insufficient spectroscopic studies on these components represents a serious obstacle in developing satellite methods to determine composition of these components in the atmosphere. Although the development of a complex method has recently been started to solve the reverse problem — in which measured data on the emitted radiation are used for an independent determination of the transmission function derivative — these developments cannot be considered sufficient for practical applications.

Studies, which have been now completed and which are related to determination of the vertical moisture distribution, showed that a serious difficulty arises in the case of "bad" weighting functions which determine the vertical distribution of the relative contribution of separate atmospheric layers to the emitted radiation (see [13]). Obviously this difficulty must also occur in determining the composition of polluting components.

Finally, we showed that all of these calculation results refer to a cloudless sky. This means that using the measured data, which pertain to real conditions, will cause the same problems related to the presence of /9 clouds, which are well known in thermal atmospheric sounding. The situation is even more complex, because the greatest interest lies in determining the concentration of polluting components near the Earth's surface.

The cloud-effect problem, in particular, might possibly be solved by using the microwave region of the spectrum, as in the case of the thermal sounding problem. However, in the microwave region the multiple lines of the separate atmospheric components significantly overlap in this region, and make the use of the microwave region much more difficult.

Finally, it can be concluded that using spectral data from the emitted thermal radiation in the infrared region of the spectrum is more promising, from the point of view of developing satellite methods for determining polluting atmospheric components. The available data show that, in spite of the many difficulties, the efforts to develop such a method should lead to fruitful results.

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